Coupled Gravity and Elevation Measurements of Ice Sheet Mass Change

Final report

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Abstract

During June 2003, we measured surface gravity at six locations about a glaciological measurement site located on the South-central Greenland Ice. We operated a GPS unit for 90 minutes at each site – the unit was operated simultaneously with a base station unit in Sondrestrom Fjord so as to enable differential, post-processing of the data. We installed an aluminum, accumulation-rate-pole at each site. The base section of the pole also served as the mount for the GPS antenna. Two gravimeters were used simultaneously at each site. Measurements were repeated at each site with at time lapse of at least 50 minutes. We measured snow physical properties in two shallow pits

The same measurement sites were occupied in 1981 and all were part of a hexagonal network of geodetic and glaciological measurements established by The Ohio State University in 1980. Additional gravity observations were acquired at three of the sites in 1993 and 1995. Gravity data were collected in conjunction with Doppler satellite measurements of position and elevation in 1981 and global positioning system measurements subsequently. The use of satellite navigation techniques permitted reoccupation of the same sites in each year to within a few 10's of meters or better. After detrending the gravity data, making adjustments for tides and removing the residual effects of local spatial gradients in gravity, we observe an average secular decrease in gravity of about 0.01 milligal/year, but with tenths of milligal variations about the mean trend. The trend is consistent with a nearly linear increase in surface elevation of between 7 to 10 cm/yr (depending on location) as measured by repeated airborne laser altimeter, surface Doppler satellite and GPS elevation measurements. Differences between the residual gravity anomalies after free air correction may be attributable to local mass changes.

This project is a collaboration between the Byrd Polar Research Center of the Ohio State University and the Arctic Technology Center of the Danish Technical University.

1 Introduction

Airborne topographic lidar data collected over south-central Greenland indicate that ice sheet thickening continued at least through 1998 at a rate between 5 to 10 cm per year. We believe it is important to understand the significance of ice sheet elevation change in terms of ice sheet mass change. Combining repeat altimeter and gravity data provides a mechanism to separate actual mass changes on the ice sheet from changes in near surface density.

During June, 2003, we measured surface gravity at six locations about a glaciological measurement site located on the South-central Greenland Ice Sheet (figure 1). Previously, gravity observations were made at the 5 of the sites in 1981 (Jezek and others, 1985), at two of the sites in 1993 and at two of the sites in 1995 (figure 2). We made measurements on a hexagonal network with vertices spaced at 20 km from the center point (van der Veen and others, 2000). Gravity data were collected in conjunction with Doppler satellite measurements of position in 1981 and global positioning system measurements in 1993, 1995, and 2003.

The measurements were made to investigate whether temporal decreases in gravity observed between 1981 and 1995 (Jezek and others, 2002) continued to the present. The goal of the measurements is to determine whether changes in gravity can be used to estimate changes in the local ice sheet mass. Three-dimensional GPS measurements were simultaneously made at each site so as to remove the free-air gravity anomaly from the gravity observations.

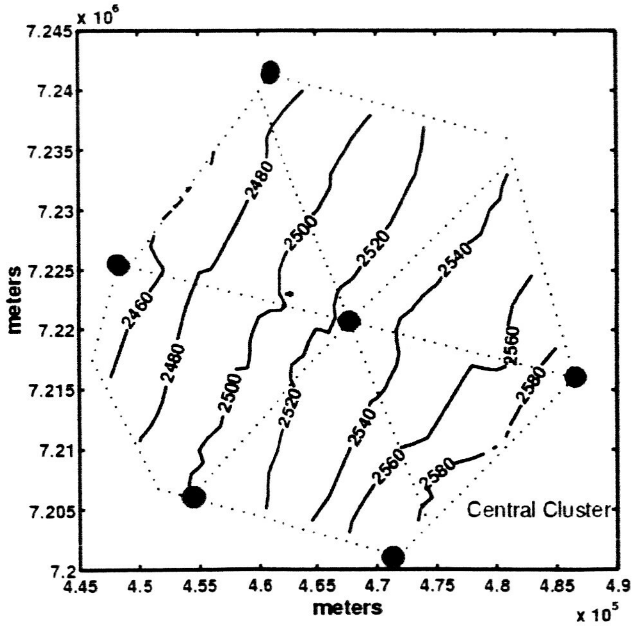


Figure 1. Surface elevation measured in 1981. Red circles show gravity sites occupied in 2003. Blue dots show shallow pit sites sampled in 2003.

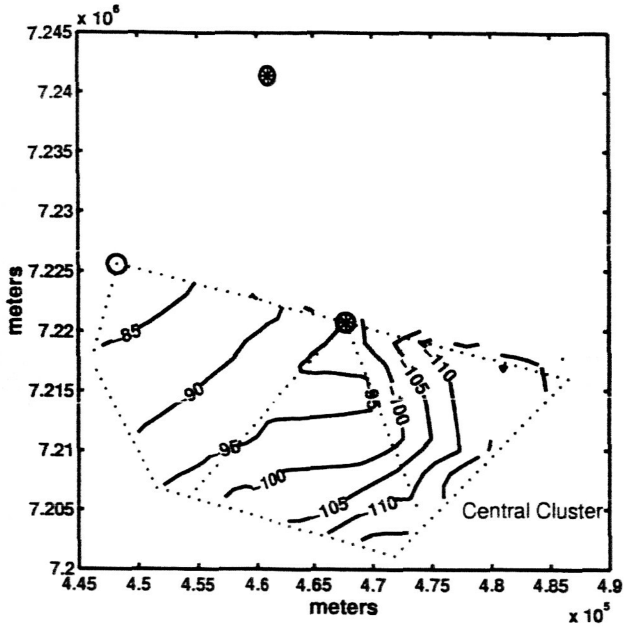


Figure 2. Relative gravity contours measured in 1981. Black dots show locations of gravity sites in 1981. Gravity sites in 1993 and 1995 are shown by circles and asterisks.

2 Measurement Time-line

We arrived in Sondrestrom Fjord on June 6. We organized equipment and measured relative gravity at the Arctic Hotel and SAS Garage IGSN sites (see section 4). Due to favorable weather conditions and advantageous scheduling, we were able to begin observations early on June 7. Prior to departure, we tied the gravity meters to the Arctic Hotel and SAS garage sites and began recording GPS data at the base station in Sondrestrom located at the Met Shack (see section 3). We flew to our first three sites using a Twin Otter aircraft. The flight time was approximately 1.5 hours. We noticed little melting on the ice sheet surface on the way to the sites (figure 3 and 4). We benefited from exceptional weather conditions (unlimited visibility, cloud-free skies, no wind, and warm temperatures) and we were able to complete three of our sites (2001, 2005, 2006). We optimized our time on the ground by deploying one receiver at station 2006, making gravity measurement, and then leap-frogging to station 2005 and 2001. We remained at 2005 for a full 90 minutes before proceeding to station 2001. We made gravity measurements upon arrival and before departure. We noticed a potential problem with early GPS data collected at 2001 (we operated an Iridium Satellite phone too close to the GPS receiver) and so spend a little more time than 90 minutes at this station to make up for any potentially noisy data. We sampled the near surface snow at 2001. We returned to 2006 to pick up the GPS receiver and to make another set of gravity measurements. We reoccupied the Arctic Hotel and SAS Garage IGSN gravimetric base stations upon return to Sondrestrom.

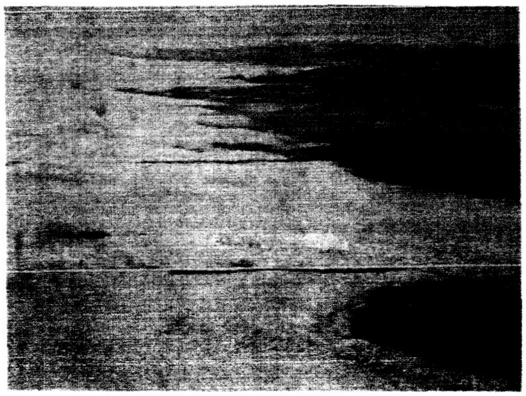


Figure 3. Ice sheet margin

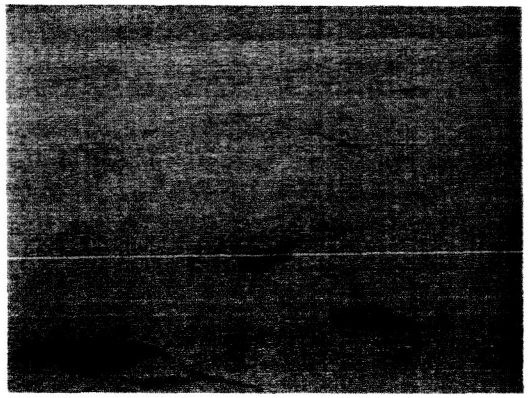


Figure 4. Surface lakes

Unexpectedly, we were also able to use the Twin Otter on Sunday, June 8. However the weather was less favorable. Consequently, our departure was delayed until about 1200 and it was still not certain as to whether we could land at our observations sites. In fact, the weather at two of the sites was reasonable (although somewhat colder and windier than the previous day) while the third site was obscured by fog early in the trip (the fog cleared at the end). We were once again able to complete three of the sites (2003, 2002, 2004). Because of concerns about the weather and our ability to retrieve the receivers, we stayed for a full 90 minutes at 2003 where we made gravity measurements and installed an aluminum accumulation rate pole. We proceeded to 2002 and observed a substantial improvement in the weather. Consequently we leap-frogged to 2004 where we also sampled a shallow pit. We returned to 2003 to retrieve the GPS receiver and remeasure gravity. We tied back into the IGSN base stations upon return to Sondrestrom.

We readied our equipment for return shipment on June 9. In addition we made gravity ties between the Arctic Hotel IGSN site and the old MAC Terminal site. MAC terminal was the primary IGSN station for the 1981 field campaign.

3 GPS Observations

We operated an Ashteck GPS base station at the Met Shack in Sondrestrom. The base station antenna and the Met Shack are shown in figures 5 and 6. The antenna is located directly above a fiducial mark.

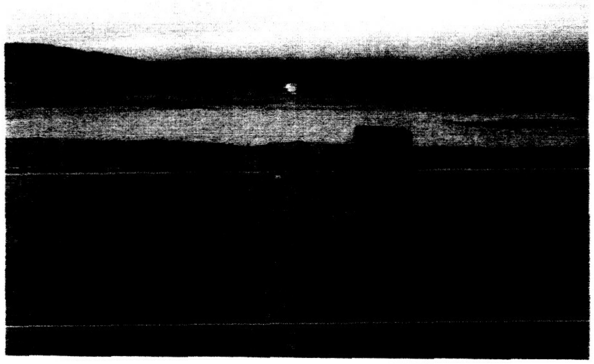


Figure 5. Met Shack located just down the fjord from the Arctic Hotel.

Figure 6. GPS base station antenna set up above the fiduical mark near the Met Shack.

We recorded data once every 30 seconds at the base station and at the field sites.

At the field sites, we drove a 6-foot aluminum pipe into the snow and mounted an antenna atop it (figure 7). We operated the GPS unit for about 90 minutes at each site. At the conclusion of the measurements, we attached a second 6-foot length of pipe to the top of the first, and measured the total height above the snow surface.

Figure 7. Gravity and GPS measurements at the field site.

Table 1. GPS Observation Summary

File Name	Date	Time	Site	Unit	Ant Hieght (cm)	Start Time	Lat	Long	Elev	PDOP	#SVs	Time off	Accum Pole
B0007	7-Jun	7:07 local	Sonde Base	2731	119.2 cm dia/ vertical hieght computed to be 124.3 cm	07:15 local	67 00.35761	50 42.19441	77.2 m	2.76	7	21:27 GMT	none
2006	7-Jun	10:06 local	2006	2733	108.8 A, 108.8E, 108.8 G	12:08 GMT	65 17.58818	45 50.03739	2475 m	2	10	15:37 local	112 inches
2005	7-Jun	11:05 local	2005	5193	124G, 123.6 E, 123.4 B	13:06 GMT	65 08.94767	45 06.22401 N.B. errorShould be 46	8075 ft	2	7	14:35 GMT	111 inches
2001	7-Jun	13:16 local	2001	5193	See below	15:17 GMT	65 06.51236	45 41.20881	8329.9 ft	2	11	13:46 local	see below
201B	7-Jun	13:46 Local	2001	5193	117.4E, 117.3C, 117.7 A	15:46 GMT	65 06.51310	45 41.20923	8334.8 ft	1	12	17:02 GMT	115 inches
B008	8-Jun	08:50 Local	Sonde Base	2731	119.2 Dia/ 124.3 cm vert	10:51 GMT	67 00.35866	50 42.19280	78.3 m	2	7	20:50 local	none
2003	8-Jun	14:15 local	2003	5193	133.0E, 133.2C, 132.7A	16:17 GMT	64 55.96538	45 35.77028	8460.3 ft	2	11	17:43 GMT	72 inches +126
2002	8-Jun	16:18 local	2002	2733	138.8H, 140.3B, 138.8 E	18:22 GMT	65 04.03927	45 17.24207	2602.5 m	2	10	20:50 GMT	132 cm +72 in
2004	8-Jun	17:02 local	2004	5193	121.7H, 119 E, 121.5 B	19:02 GMT	64 58.89729	46 01.58124	8223.2 ft	1	12	20:27 GMT	115cm+72 in

4 Gravity Measurements

We used two Lacoste Romberg model G land gravity meters. We tied our surveys to two IGSN stations in Sondrestrom, the Arctic Hotel (figure 8) and the SAS Garage (figure 9).

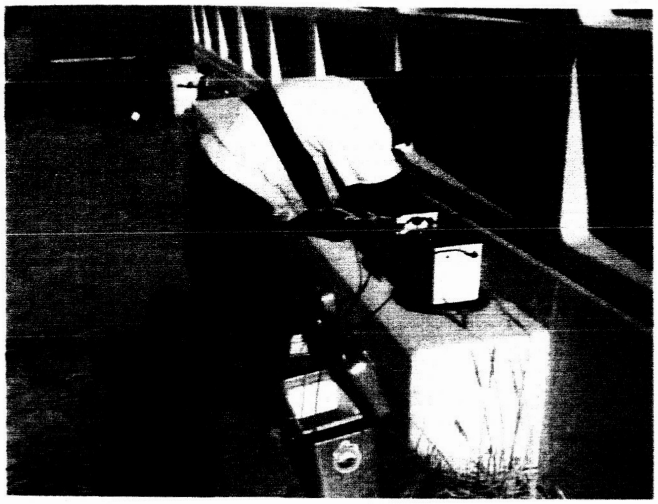


Figure 8. Arctic Hotel IGSN station nr. 68202, EPB 9143-82. A brass fiducial marker indicates the site.

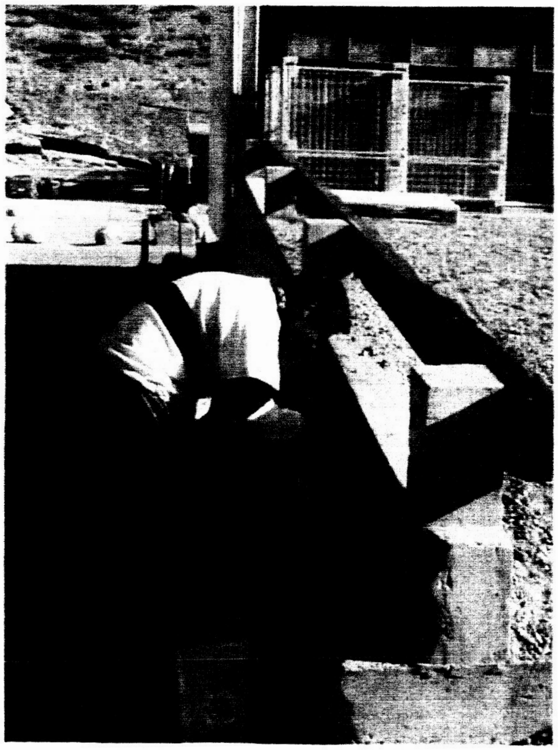


Figure 9. IGSN site at the SAS garage, station nr. 68201, EPB 9122-82.

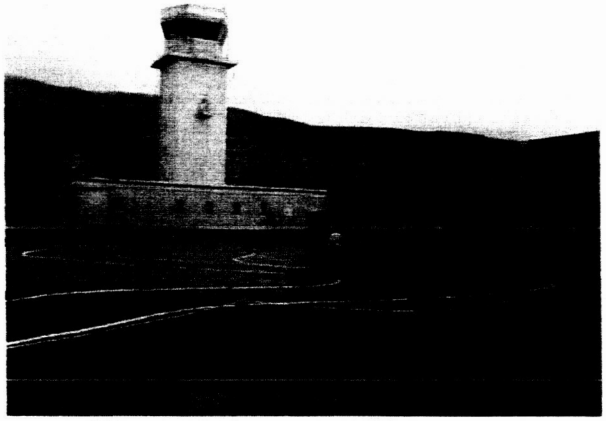
We made measurements with both gravity meters at the base stations and at the field sites. We used a wooden platform mounted flush with the snow surface and near the GPS antenna in the field. We were able to maintain gravity meter temperatures throughout the campaign and drift less than 0.12 mgal per day.

The following table shows the preliminary estimates of absolute gravity values measured in 2003 at all sites with the G-867 gravimeter. The raw data have been reduced so as to correct for the instrumental drift and the tidal effect. A comparison is made with previous absolute values derived in 1981.

Table 2. Preliminary Absolute Gravity Values and Comparisons

Year	Station	Abs g	Elev	(Y2003 - Y1981)
1981	2001	981604.287		0
1993	2001	981603.827		-0.46
1995	2001	981604.26		-0.027
2003	2001	[redacted]		-0.197
1981	2002	981581.464		0
1993	2002	no value		
1995	2002	no value		
2003	2002	[redacted]		-0.189
1981	2003	981580.775		0
1993	2003	no value		
1995	2003	no value		
2003	2003	[redacted]		-0.445
1981	2004	981605.03		0
1993	2004	no value		
1995	2004	no value		
2003	2004	[redacted]		-0.3
1981	2005	981617.24		0
1993	2005	no value		
1995	2005	981616.67		-0.57
2003	2005	[redacted]		-0.26
1981	2006	no value		
1993	2006	981610.359		
1995	2006	981610.35		
2003	2006	[redacted]		

At the end of the campaign, we also tied the Arctic Hotel IGSN gravity site into the old MAC terminal IGSN site (figure 10 and 11). We did this because MAC terminal served as the primary absolute gravity site for the 1981 campaign.



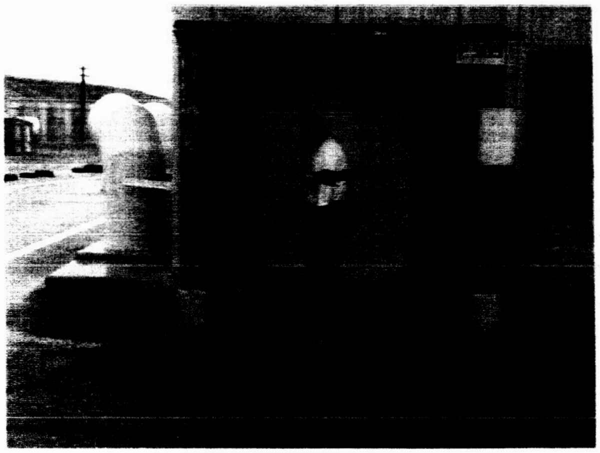


Figure 10. MAC Terminal 68203, EPB 9843-65.

Figure 11. MAC IGSN station nr.

5 Shallow Pits

We sampled the near surface snow on June 7 at 2001 and dug a shallow pit at 2004 on June 8. The temperature profiles are shown in figure 12 and 13. Firn stratigraphy for 2004 is shown in figure 14. The stratigraphy is difficult to interpret because of the numerous ice layers found near the surface. Observations of the surface during the flight to the site suggested that the ice sheet has not yet started appreciable summer melt. But if so, then there was virtually no accumulation during the past winter. We will examine passive microwave data for the site to determine whether a low accumulation scenario or an early melt scenario is more plausible.

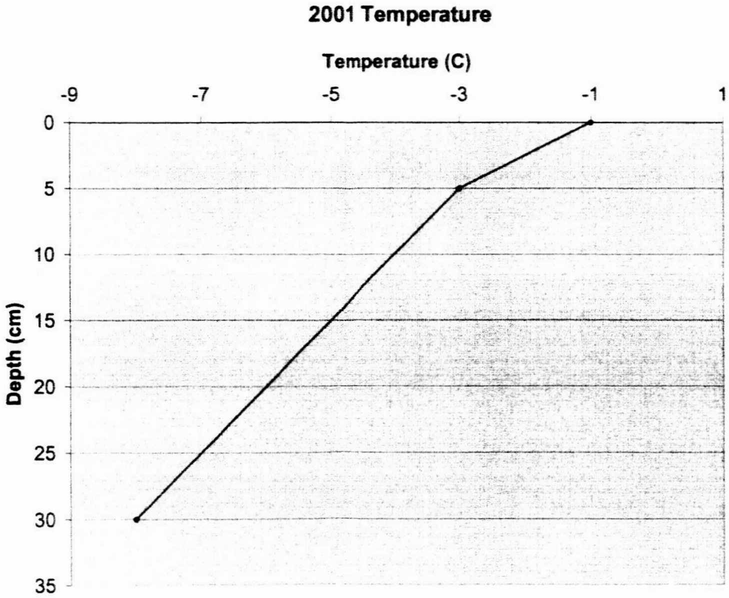


Figure 12. Snow Temperature at 2001

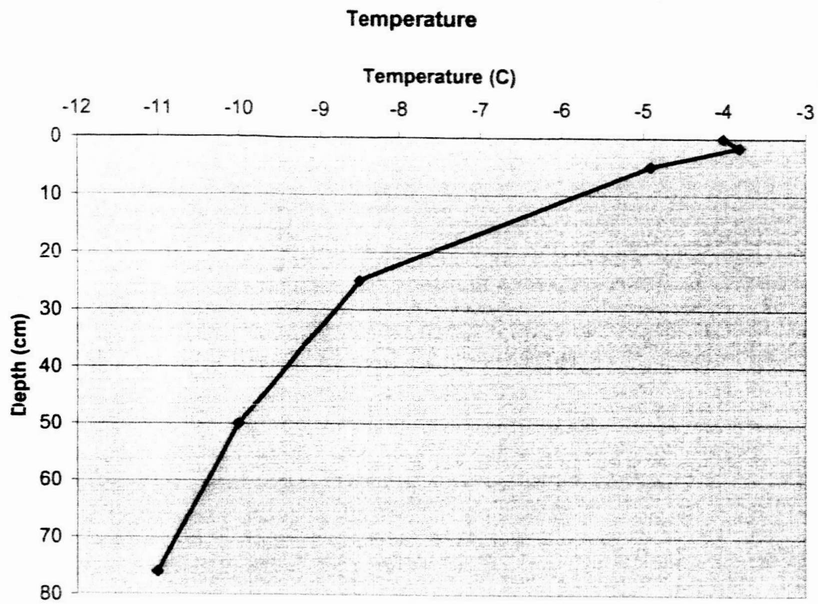


Figure 13. Snow temperature at 2004.

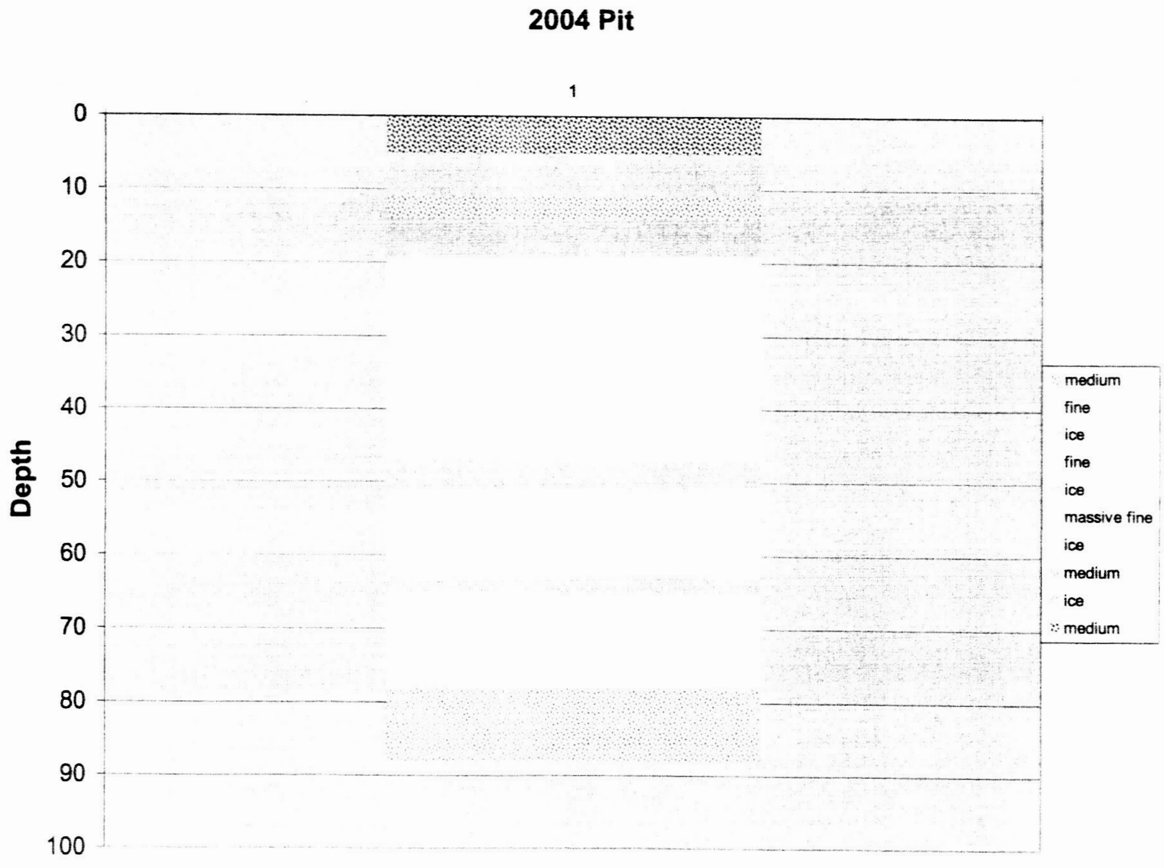


Figure 14. Firn stratigraphy at 2004.

6. Results

GPS data were analyzed under the direction of W. Krabill of Wallops Flight Facility. Measured changes in surface elevation are shown in figure 15. The surface elevation at each site is monotonically increase at a rate between 7 to 10 cm per year.

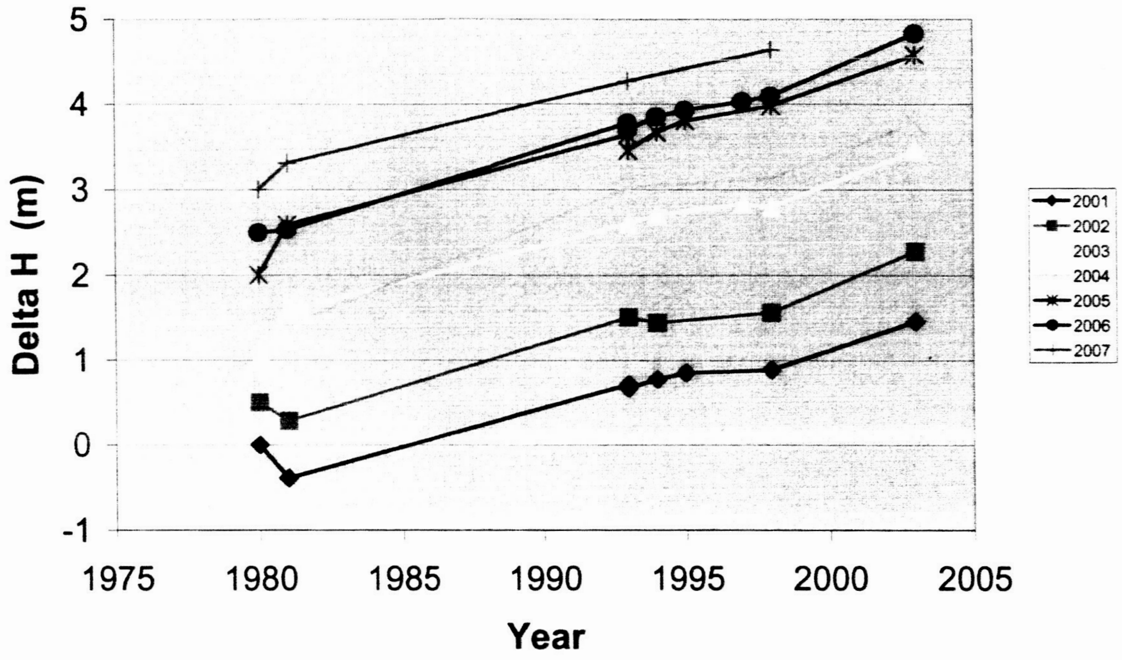


Figure 15. 24-year record of elevation changes at the Central Cluster site.

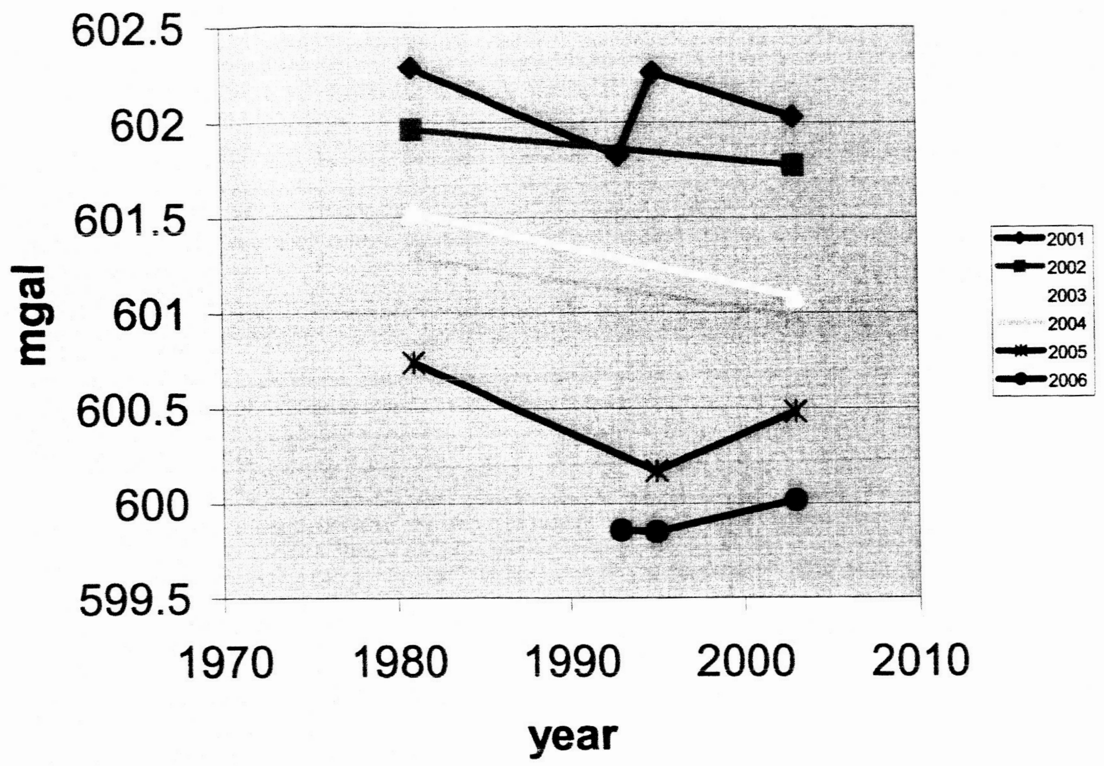


Figure 16. 24 year record of gravity changes at the Central cluster site.

Annual changes in surface gravity are shown in figure 16. The signal is more complex than the elevation data, partly because of the small signal we are trying to measure. Repeated gravity measurements at the same site, made as part of the standard procedure when occupying a site, are typically consistent to about 0.02 mgal. Measurement error compounded with instrument drift and tares might easily double this value.

Using standard free-air gravity corrections and Bouguer slab model, we can combine the elevation trends with the gravity trends to estimate the change in mass at the site. Using all of the data we estimate an increase of mass of between 318 and 1025 +/- 160 gm/cm^2 which reflects variation between stations. On average this corresponds to an increase of about 35 gm/cm^2/yr. This is slightly less than the modeled accumulation rate (J. Box, personnal communication.

7. Summary

We completed all of our gravity and GPS measurement goals. Initial results suggest that the data are of excellent quality. We also measured snow physical properties at two-sites. We were limited in physical property measurements by a competing demand to maintain short intervals between gravity base station readings and to keep the meters on heat.

Our analysis shows that:

- Trends of in situ GPS, Airborne Lidar and Gravity data all consistent with an increase in surface elevation at Central Cluster over 2 decades (about 7-10 cm/yr)
- Over the two decades gravity values predict an increased load of 770 +- 160 gm/cm2 and an averaged load change of +35 gr/cm2/yr
- But for shorter time variations both increase and decrease of mass are observed (but with large error on the estimates).
- Refined techniques developed in 2003 combined with NASA's ATM and IceSAT elevation data and with new NSF- purchased gravity meter should reduce uncertainties

8. References

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